Application Of The Sitar Model For Estimating Age At Peak Height Velocity, Peak Height Velocity, And Adult Height From Incomplete Growth Curves In Elite Male Football Players

Xabier Monasterio, [1 2] **Mikel Pérez-Arrieta,** [3] **Dae-Jin Lee,** [3 4] **Jon Larruskain** [1]

[1]Athletic Club, Lezama, Spain
[2]University of the Basque Country (EHU), Leioa, Spain
[3]Basque Center for Applied Mathematics (BCAM), Bilbao, Spain
[4]IE University, Madrid, Spain

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Headline

We examined the accuracy of the SITAR model for estimating APHV, PHV, and adult height from incomplete height data in elite male football players. SITAR provided the most precise APHV estimates and similar adult-height accuracy to KR and TW2, outperforming commonly used maturity offset and ratio equations, supporting its use in player development and injury-risk management.

Aim of the paper

This report aimed to evaluate the accuracy and precision of the SITAR model for estimating age at peak height velocity (APHV), peak height velocity (PHV), and adult height from incomplete longitudinal height records in elite male football players. We also compared SITAR-derived estimates with those obtained from commonly used somatic maturity equations and we developed an online calculator to facilitate the practical application of SITAR-based estimations in football academy settings.

Methods

Participants and study design

We retrospectively studied the growth data of Athletic Club's academy football players who were regularly monitored from the 2000–2001 to the 2021–2022 seasons. We took measurements as part of the regular programme at the academy under the supervision of the medical staff. All data collection was conducted in accordance with the principles of the Declaration of Helsinki.

Anthropometric assessment

We measured stature and mass using a portable stadiometer (Añó Savol, Spain) and a portable weighing scale (Seca Bonn, Germany) every 3 to 6 months. Sitting height was measured using a stool of standardised height as part of a longitudinal study from the 2009–2010 season through the 2015–2016 season (1). The same three assessors measured standing height and mass across the entire study period, and one assessor measured sitting height throughout the study period. The estimated intra- and inter-observer technical error of measurements for stature were 0.23 and 0.29 cm, respectively. The intra-observer technical error for sitting height was 0.14 cm.

Observed APHV, PHV and adult height

We fitted the longitudinal height records for each player with the SITAR model (2) to calculate APHV (years) and PHV (cm/year). To ensure a high temporal interval around the adolescent growth spurt and thereby precise calculations, only players with at least 10 observations before and after the estimated APHV were included in this analysis (n = 124; 119 of European ancestry, 5 of non-European ancestry). On the basis of individual APHV, we determined pre-, circa- or post-PHV intervals using both ± 1-year and ± 0.5-year thresholds for circa-PHV. We recorded observed adult height when a player was growing at <1 cm/year for 1 year.

Estimations from incomplete growth curves using SITAR

We formed a total of 2560 incomplete growth curves by removing data points from the complete growth curves of the 124 players included in the study. These incomplete growth curves were used in a previous paper to study an expert clinician's ability to visually assess incomplete growth curves (3). The initial height measurements of the incomplete growth curves varied from U11 to U15, whereas we took the last measurements in U13, U14, or U15 age groups.

We modelled incomplete growth curves with SITAR (2), which relies on a population's average trajectory to fit individual growth data. We used the 124 individual growth curves included in the study (football-specific population) and the Berkeley Growth Study's dataset (Caucasian children born in California in 1928–1929) (4) as reference populations to estimate APHV, PHV and adult height. When using the football-specific dataset for estimations, we left out the growth data of the player for whom the incomplete growth curve was being estimated from the reference sample to assess out-of-sample predictive ability (leave-one-out cross-validation analysis) (5). We estimated adult height as height at the age of 18 (the last height measurement in the Berkeley Growth Study).

Estimated APHV using maturity offset equations and maturity ratio

We estimated APHV using the original Mirwald equation (Mirwald et al., 2002), the first Moore (7) equation, and Fransen's maturity ratio (8) in players for whom both standing and sitting height measurements were available (18 players and 85 observations). The second Moore et al. (7) equation, which includes age and height, was used to estimate APHV for all height measurements of the players.

Adult height estimation using KR and TW2

We used the KR equation (9) to estimate the adult height of players for whom parental heights were available (43 players and 435 observations). We adjusted self-reported parental heights for overestimation (10). The equation utilises the chronological age, height, and weight of the player and the midparental height.

We also estimated adult height with the TW2 radius–ulna–short bone protocol (11) for players for whom radiographs were taken at the beginning of the U14 season (78 players/observations). Two experienced trained doctors interpreted the images, who showed intra- and inter-observer errors of 0.10 and 0.25 years, respectively, when calculating skeletal age. We estimated adult height using stature, skeletal age, and chronological age at the time of observation.

Data analysis

We calculated the mean difference and standard deviation (SD) between estimated and observed APHV, PHV, and adult height to assess each method's accuracy and precision. Furthermore, we used Bland-Altman graphs to plot the difference between observation and estimation over the average of these two, with ±1.96 SD lines (95% confidence interval) parallel to the mean difference line. Moreover, we calculated the percentages of concordance between observed and estimated maturity status classifications (pre-, circa-, and post-PHV) for the SITAR model (2).

Results

According to the complete records for the 124 players, the mean ages at the initial and final observations were 10.7 ± 0.6 and 18.7 ± 2.5 years, respectively. Each player had 16 ± 3 height measurements. APHV occurred at 13.5 ± 0.9 years, and PHV was 10.1 ± 2.0 cm/year. Players attained adult stature at 19.5 ± 2.2 years, reaching 179.5 ± 5.1 cm. Regarding APHV, estimations from incomplete growth curves using SITAR showed almost no systematic error, as the mean difference between the estimated and observed APHV was near 0 for both the football-specific and Berkeley datasets (Table 1 and Figure 1). The Mirwald and Moore-1 equations and the maturity ratio showed a systematic overestimation of approximately 1 year, whereas the Moore-2 equations showed a slight overestimation. Further, the SDs were lower with the SITAR method (±0.6 years) than with the maturity offset equations and maturity ratio (approximately ±0.9 years) (Table 1).

We observed that the estimations of PHV from the SITAR model using the football-specific population showed a systematic underestimation of 0.50 cm/year and wide variability (SD: ±1.78). The underestimation of PHV was even more evident with the Berkeley dataset (-1.08 ± 1.82) (Table 1).

Concerning adult height estimation, SITAR slightly underestimated adult height (-0.33 and -0.05 with the football-specific and Berkeley datasets, respectively), while TW2 at U14 and KR slightly overestimated adult height (0.91 and 1.66 cm, respectively). The SD for adult height estimations was approximately ±3–4 cm with all methods.

The SITAR method tended to normalise the estimations of all three parameters, overestimating the lowest values and underestimating the highest values (Figure 1). This pattern was particularly pronounced for PHV. The age group at the last and first height measurements also influenced the accuracy and precision of the SITAR estimations. We observed that the parameters tended to be overestimated in the U13 age group but underestimated in the U15 age group. This pattern was most evident for PHV. Moreover, the SDs tended to be lower when longer longitudinal recordings were available (Table 2). This trend was similar when using the Berkeley dataset as the reference population (Table 3).

Maturity status classifications (pre-, circa-, and post-PHV) using the SITAR method with the football-specific dataset showed 80% and 84% of concordance using ±1 and ±0.5 year criteria for the circa-PHV interval, respectively. Similar results were found when using the Berkeley dataset as a reference population (81% and 83% using ±1 and ±0.5 year criteria for the circa-PHV interval, respectively). A higher percentage of concordance with longer longitudinal recordings in all U13, U14, and U15 categories was observed. When a single growth velocity was available (U13–U13, U14–U14, and U15–U15), a lower percentage of concordance was found in U14 (73% and 63% with ±1 and ±0.5 year criteria, respectively) compared with U13 (74% and 75%) and U15 (77% and 87%) (Table 4). The results were similar for the Berkeley dataset (Table 5).

Table 1. Mean difference and standard deviation of estimated vs. observed age at peak height velocity, peak height velocity, and adult height for each maturity estimation method.

	APHV (years)		PHV (cm/year)		Adult height (cm)	
METHODS	Mean difference	SD	Mean difference	SD	Mean difference	SD
Mirwald	1.09	0.87				
Moore-1	0.80	0.85				
Moore-2	0.14	0.95				
Fransen	1.30	0.95				
Tanner-Whitehouse-2 in U14					0.91	3.47
Khamis-Roche					1.66	3.66
SITAR Football	-0.09	0.57	-0.50	1.78	-0.33	3.06
SITAR Berkeley	-0.04	0.62	-1.08	1.82	-0.05	3.64

APHV: age at peak height velocity
PHV: peak height velocity
SITAR: Superimposition by Translation and Rotation
SD: standard deviation

Table 2. Mean difference and standard deviation of estimated vs. observed age at peak height velocity, peak height velocity, and adult height from incomplete growth curves using SITAR with the football-specific dataset for players in the U13, U14, and U15 age groups.

	APHV (years)						PHV (cm/year)						Adult height (cm)					
	U13		U14		U15		U13		U14		U15		U13		U14		U15	
First height measurement	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD
U11	0.01	0.38	-0.05	0.45	-0.07	0.44	-0.53	1.87	-0.58	1.46	-0.67	1.47	0.20	3.05	-0.53	3.07	-0.70	2.26
U12	0.02	0.53	-0.02	0.26	-0.04	0.33	-0.68	1.80	-0.57	1.22	-0.61	1.29	0.21	4.14	-0.29	3.39	-0.67	2.24
U13	0.19	0.72	-0.17	0.78	-0.11	0.52	-0.38	2.25	-0.43	1.88	-0.50	1.91	0.15	3.47	-0.03	3.75	-0.25	1.78
U14			-0.21	0.68	-0.16	0.54			-0.28	1.89	-0.42	1.88			-0.76	3.79	-0.71	2.02
U15					0.03	0.70					-0.56	2.02					-0.54	2.45

SD: standard deviation; diff: difference; U: under; APHV: age at peak height velocity; PHV: peak height velocity.

Table 3. Mean difference and standard deviation of estimated vs. observed age at peak height velocity, peak height velocity, and adult height from incomplete growth curves using SITAR with Berkeley dataset among players in the U13, U14, and U15 age groups.

	APHV (years)						PHV (cm/year)						Adult height (cm)					
	U13		U14		U15		U13		U14		U15		U13		U14		U15	
First height measurement	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD	Mean diff.	SD
U11	0.22	0.58	0.02	0.49	-0.05	0.43	-1.31	1.99	-1.29	1.47	-1.39	1.45	1.30	5.39	-0.22	3.21	-0.68	2.22
U12	0.19	0.59	0.07	0.29	-0.01	0.26	-1.34	1.89	-1.07	1.28	-1.15	1.29	0.89	4.65	0.09	3.63	-0.48	2.24
U13	0.02	0.81	-0.07	0.77	-0.14	0.56	-1.07	2.36	-0.83	1.95	-0.88	1.94	1.65	4.62	0.28	4.14	-0.55	1.88
U14			-0.19	0.76	-0.24	0.56			-0.87	1.88	-0.87	1.81			-0.34	4.53	-1.20	1.98
U15					-0.14	0.72				2.02	-1.16						-1.03	2.33

SD: standard deviation; diff: difference; U: under; APHV: age at peak height velocity; PHV: peak height velocity.

Table 4. Percentage of concordance for maturity status classifications (pre-, circa-, and post-PHV) between observed and estimated age at peak height velocity using SITAR with the football-specific dataset with ±0.5 and ±1 year criteria for circa-PHV among players in the U13, U14, and U15 age groups.

	Classification using ± 1-year threshold for circa-PHV period			Classification using ± 0.5-year threshold for circa-PHV period		
First height measurement	U13	U14	U15	U13	U14	U15
U11	83%	83%	90%	92%	84%	91%
U12	84%	76%	91%	85%	88%	92%
U13	74%	69%	87%	75%	75%	90%
U14		73%	83%		63%	91%
U15			77%			87%

U: under; PHV: peak height velocity.

Table 5. Percentage of concordance for maturity status classifications (pre-, circa-, and post-PHV) between observed and estimated age at peak height velocity using SITAR with the Berkeley dataset with ±0.5 and ±1 year criteria for circa-PHV among players in the U13, U14, and U15 age groups.

	Classification using ± 1-year threshold for circa-PHV period			Classification using ± 0.5-year threshold for circa-PHV period		
First height measurement	U13	U14	U15	U13	U14	U15
U11	83	83	92	83	86	90
U12	79	79	94	81	85	93
U13	73	73	85	72	78	90
U14		74	83		63	91
U15			78			89

U: under; PHV: peak height velocity.

Discussion

In this study, we evaluated the accuracy and precision of the SITAR model in estimating APHV, PHV, and adult height from incomplete growth curves and compared the estimates with those obtained from available somatic maturity estimation equations.

APHV estimations from incomplete growth curves using SITAR were superior to estimations from maturity offset equations and the maturity ratio

Our results highlight the potential of SITAR estimations, which showed minimal systematic error and lower variability for APHV estimations (SD ±0.57, with 95% of estimations within ±1 year of error) compared with traditional equations, highlighting its accuracy and precision. The normalisation of APHV estimations observed with SITAR has also been described in previous validation studies of maturity offset (12–14). However, these studies reported a more pronounced normalisation effect, particularly in early maturers (APHV <12.8), whose APHV was systematically overestimated by 1.25–1.75 years. This limitation is relevant in academy football, where the proportion of early maturers tends to be high (15).

We found that the SITAR method correctly classified 8 out of 10 players as pre-, circa-, or post-PHV, similar to the accuracy of expert visual assessment (∼80%) and superior to other estimation methods such as maturity offset (∼50–70%) and the percentage of predicted adult height using the KR or TW2 equations (∼60–75%) (3). Accurate classification of maturity status is essential in football academies, since different injury patterns are observed between pre-, circa-, and post-PHV players, requiring tailored injury-prevention strategies for each group (16,17). Furthermore, longitudinal studies indicate that boys experience significant gains in functional capacity (e.g. explosive strength, power, and speed) during the interval of PHV or shortly after PHV (18,19). Thus, performance evaluation should consider maturity status to make fairer comparisons of player performance (20,21). Moreover, some circa-PHV individuals experience temporary performance regressions (i.e. adolescent awkwardness) which may influence (de)selection decisions (22,23). Therefore, methods that misclassify a large proportion of players may lead to greater injury risk, inappropriate training and comparisons, and biased talent identification processes.

In line with previous research, SITAR tended to slightly overestimate APHV in younger players (mostly pre-PHV, U13) and underestimate it in older players (circa- or post-PHV, U14–U15) (24). Nevertheless, this bias was minimal compared with the systematic overestimation reported for maturity offset and maturity ratio equations. The accuracy and precision of SITAR estimations improved with longer longitudinal height series, underlining the importance of consistent height monitoring from early adolescence. Even when only a single season of measurements was available (e.g. U13–U14), SITAR produced more accurate and precise estimations than the maturity offset equations, with a concordance rate of 63–87%, higher than previously reported for other estimation methods (3).

Better estimations of APHV by SITAR will also lead to more accurate timing categorisations of players as early, on-time, or late maturers. Thus, SITAR appears to be a superior alternative to the less accurate maturity offset and Khamis–Roche equations, both widely used in football academies (25–27), and to visual assessment, which is time-consuming and assessor-dependent.

Finally, SITAR estimations using the Berkeley reference dataset were as accurate and precise as those obtained using our football-specific dataset. This consistency highlights the model's potential for application in different populations and contexts without the need for academy-specific reference data.

APHV: age at peak height velocity; PHV: peak height velocity; SITAR: Superimposition by Translation and Rotation.
Solid lines indicate the mean difference. Dashed lines indicate ±1.96 standard deviation. Dotted lines indicate a linear trend.

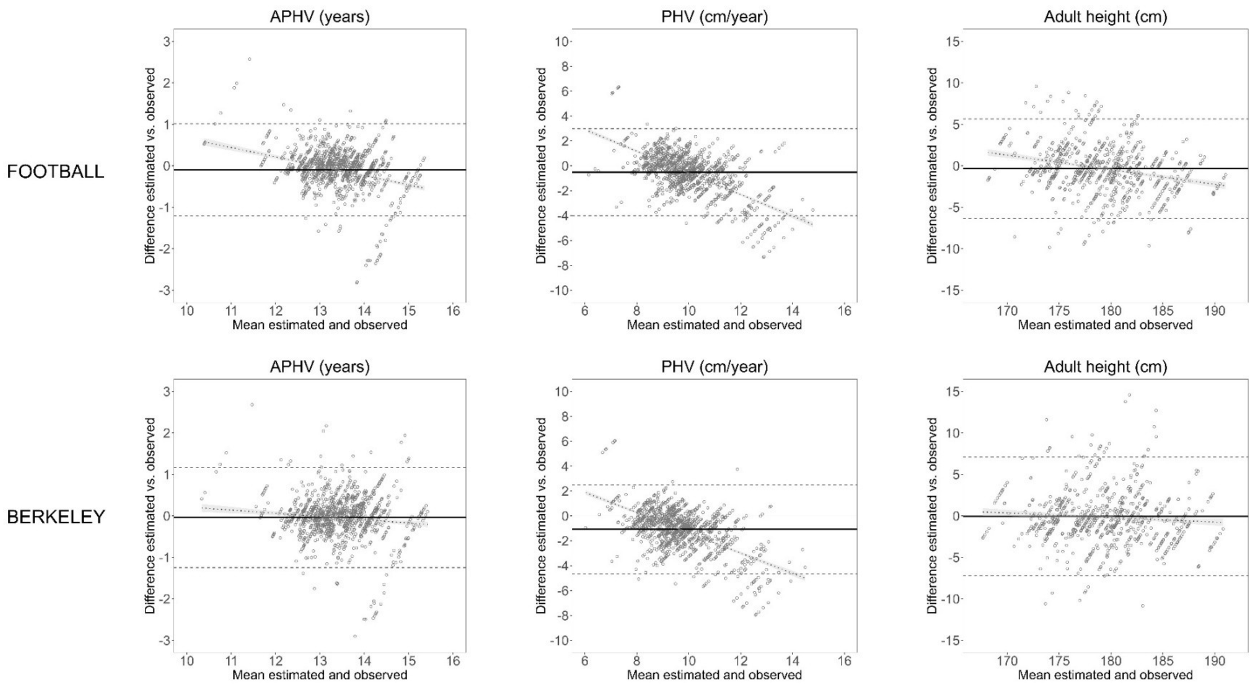

Fig. 1. Bland–Altman plots for estimations of age at peak height velocity, peak height velocity, and adult height from incomplete growth curves using SITAR with the (1) football-specific and (2) Berkeley datasets. Negative scores imply underestimation; positive scores imply overestimation.

PHV estimations from SITAR were inaccurate

Previous research in a non-sportive Czech population in the 1960s found a slight systematic overestimation of PHV with SITAR (range: 0.06–0.72 cm/year) (24); however, our results showed a systematic underestimation of PHV of 0.50 cm/year. This difference may be related to the PHV differences between the two populations. The PHV for men in the Czech study was 9.2 ± 1.2 cm/year, whereas our dataset showed a quicker PHV and a higher variability (10.1 ± 2.0 cm/year). The quicker average PHV in our players might be linked to the systematic selection of earlier maturing players with quicker PHVs (28). Considering that SITAR normalised PHV in our sample, the underestimation of PHV in players with quick PHVs may have led to a systematic underestimation of PHV. The underestimation was even more evident (-1.08 cm/year) when using the Berkeley dataset as the reference population, in which the PHV was slower than that in the football dataset (9.5 cm/year) (29). The slower PHV in the Berkeley population might be related to general improvements in health and nutritional conditions over time.

Furthermore, we found a high SD of ±1.78 years, with 95% of estimations falling within a range of error of ±3.5 cm/year. The inaccuracy and imprecision of PHV estimations may limit its applicability. Quick PHV has been linked to adolescent awkwardness (22) and a higher risk of injuries in the circa-PHV period (30). More specifically, circa-PHV players with PHVs over 10.84 cm/year showed an injury burden approximately three times higher than that of players with a slower PHV (30). Considering the systematic underestimation and precision of PHV estimations, it would be difficult to detect players with quick PHV and apply strategies to reduce injury risk (31); therefore, better models to estimate PHV are needed.

Similar accuracy and precision of adult height estimations were found with SITAR, KR, and TW2

Adult height estimation is common practice in football academies to guide (de)selection decisions, especially for goalkeepers, defenders, and central strikers, positions for which height is key in selection processes (32).

Estimations of adult height from incomplete growth curves using SITAR showed an error similar to that using KR and TW2, even when the incomplete growth curves only spanned one season. Our results showed that the SITAR method tended to slightly overestimate adult height in U13 players (mostly pre-PHV) and underestimate it in U14 and U15 players (mostly circa- and post-PHV); however, in all categories, the error was similar to the mean error in the abovementioned adult height estimation equations. The SD for estimations using SITAR with football-specific population reference was ±3.06, indicating that 95% of estimations would be within 6 cm of error. Furthermore, the SD for adult height estimations was narrower in players who were older (U13 > U14 >

U15) and those with longer longitudinal height recordings (e.g. from U11). This highlights the potential of the SITAR method compared with KR and TW2, as it does not require parental height or the evaluation of an X-ray. Moreover, it allows for improved estimations with longitudinal recordings of growth compared with X-rays that might not be repeated because of their invasiveness.

Practical applications

- SITAR offers more accurate APHV estimations than maturity offset and ratio equations, improving maturity-status classification in academies even with shorter height series, though accuracy improves with longer monitoring.
- More precise maturity information can support better training individualisation, injury-risk management, and fairer performance comparisons during adolescence.
- Adult height estimations using SITAR match KR and TW2 without requiring parental heights or X-rays.
- We present an online maturity calculator (`http://growth.athletic-club.eus:3838/app/`) which allows quick, user-friendly APHV, PHV, and adult-height estimations and downloadable reports for practical decision-making.

Limitations

- Findings are based on male Basque academy football players and may not generalise to other sports, ethnicities or competitive contexts.
- PHV estimations showed high variability and systematic underestimation, limiting their practical use.
- Future methodological improvements, such as machine learning approaches, may help refine PHV and adult-height estimations.

Conclusion

This study shows that the SITAR model provides accurate and precise estimations of APHV, PHV, and adult height from incomplete longitudinal height data in adolescent football players. Compared with the maturity offset method, SITAR showed lower systematic error, reduced variability, and improved classification of maturity status. While PHV was systematically underestimated, adult height estimations showed similar accuracy and precision to those obtained with the Khamis–Roche and Tanner–Whitehouse 2 methods. Overall, SITAR provided a more accurate classification of maturity status than methods based on percentage of predicted adult height, supporting its use as a practical and objective tool for monitoring growth and maturation in academy settings.

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